

High Precision Industrial Wireless LAN System with Asynchronous Communication

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Abstract—In this paper, we propose an industrial Wireless Local Area Network (iWLAN) system compatible with asynchronous communication for industrial robots (iRBs) control in factory automation (FA) environments. The design of our media access control layer is synchronous multi-user round-robin transmission protocol. Low overhead Packet Division Multiple Access (PDMA) scheme is utilized for Multi-user Downlink transmission up to 80 MHz, while Frequency Division Multiple Access (FDMA) is employed for the uplink transmission. The system is developed based on a fast and deterministic communication featuring the synchronous multi-user system. In general, the iRBs are not only controlled by synchronous communication but also by asynchronous communication via this iWLAN system. In this paper, we present the Field-programmable gate array (FPGA) implementation are carried out to confirm that our iWLAN system by asynchronous communication can control up to four motors. Based on the result of FPGA implementation, the time synchronization of the proposed system in high accuracy from 40 to 100 ns is also captured by an oscilloscope.

Keywords—Asynchronous, iWLAN, FPGA Implementation, Motor Control, Time Synchronization.

I. INTRODUCTION

In recent years, wireless technology has emerged as a promising alternative for industrial communication because it can provide the flexibility for mobile terminal settings (e.g. robots, actuators, sensors, etc.). Many studies related to industrial wireless communication system were discussed such as positioning for industrial wireless LAN (iWLAN) [1] or coexistence of iWLAN in the context of industries 4.0 [2]. Wireless technology also offers advantage for the factory automation (FA) systems because it can reduce physical connectivity (cable or wiring), resulting in a lower maintenance cost [3]. There are several solutions for FA wireless communication, include Bluetooth for short-range transmission applications [4]; ZigBee that is suitable for sensor network [5]; and industrial communication standard WirelessHART [6] that improves data rate and reliability of ZigBee. However, the poor compatibility with IEEE 802.11 WLAN devices such as in WirelessHART, make those devices are difficult to co-operate with standard office devices such as PCs, laptops and mobile phones in the factory environments, where the wireless LAN connection is a legacy wireless communication. To address these requirements, PROFINET has offered an industrial WLAN system using an industrial point coordination function (iPCF) protocol [7]. Unfortunately, this protocol can only achieve low throughput since the protocol employs Time Division Multiple Access (TDMA) scheme and support single

user (SU) transmission. Hence, in a dense network such as FA environment, that involves many robots (terminals), the performance of this protocol cannot satisfy the real-time requirement as required in the FA system.

The novel iWLAN protocol is proposed to address the limitation of iPCF protocol, as presented in [8]. This protocol introduces low overhead multiple-access Downlink (DL) and Uplink (UL) transmission scheme for the fast communication system. Packet Division Multiple Access (PDMA) transmission scheme with multi-user access is employed for DL communication, while Frequency Division Multiple Access (FDMA) is employed in UL transmission. This transmission protocol can significantly eliminate the overhead and able to achieve high throughput. The analysis and simulation results show that our proposals provide 100% better throughput than the conventional iPCF [9], [10].

The deployment of our iWLAN system to control motor is necessary to prove the ability of the system. In general, there are two types of communication system for controlling the industrial robot (iRB): synchronous communication and asynchronous communication. From the middle of 1980's, serial communication such as RS232-C, RS-422, and RS-485 has been used for monitoring system in FA. Until now, the asynchronous communication using several communication standards are still widely employed [11]. The proposed system controls the robot by synchronously communicating the MS and access point (AP) to the station (STA) and iRB in a fixed cycle called Control Duration. Each pair of MS-AP and STA-iRB performs communication by using Industrial Ethernet, while communication between AP-STA is carried out through iWLAN system. This Industrial Ethernet communication is performed at the same time that implies AP and STA always have data to be exchanged after this Industrial Ethernet communication phase. We suppose to control the timing of transmitting data by an interrupt signal, notifying the end of the fixed cycle (Control Duration) from medium access control (MAC) hardware. However, in the case of asynchronous communication, the central processing unit (CPU) cannot transmit data because the CPU cannot determine the timing when the data is received, even if an interrupt has been received. Although we can transmit data in interrupts of the next cycle, the conventional proposed system causes an overhead due to memory writing. It threatens the real-time performance which is one of the demands of iRBs. Therefore, a memory writing technique that corresponds to asynchronous communication is proposed. Furthermore, we offer a motor

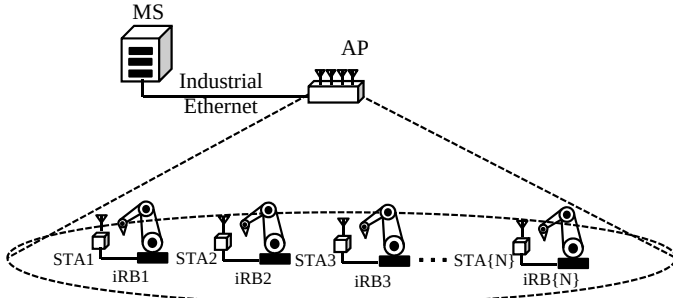


Figure 1. FA-WLAN System Model

control up to 4 motors via an asynchronous system based on 1 AP 2 STAs 20MHz. The time synchronization of 1 AP 2 STAs is also presented in this paper.

The rest of the paper is organized as follows. In Section II, we discuss the FA wireless communication system model with the proposed transmission protocol. Section III present our proposed precision time protocol. In Section IV, asynchronous communication with the proposed memory writing technique is explained. In Section V, FPGA implementation results of the proposed system are shown. Lastly, we conclude this paper in Section VI.

II. FA-WLAN COMMUNICATION SYSTEM OVERVIEW

The FA wireless communication system includes a Master Station (MS) and several industrial Robots (iRBs), as illustrated by the system model in Fig. 1. Access Point (AP) is installed to MS and Stations (STAs) are connected to iRBs. AP communicates to STA in wireless and transmits the orders of MS to iRB. The data transmission occupies signal bandwidth up to 80 MHz. The FA wireless communication system supports the deterministic transmission feature, in which the communications from MS to each iRB are in equal portions and circular order without priority.

A. FA-WLAN Communication Protocol

Fig. 2 shows the protocol diagram of our proposed iWLAN. The sequence operation of the protocol includes three stages:

- Stage 1 (SYNC): MS starts a new control duration (T_{cd}) by broadcasting a synchronization (SYNC) frame to all iRBs on the bandwidth of 20/40/80 MHz. This SYNC frame carries the information of the Precision Time Protocol (PTP). The duration of SYNC frame transmission is denoted by T_{sync} .
- Stage 2 (COMMUNICATION): MS communicates with all N iRBs. This communication duration is denoted by T_{com} . This interval includes the following operations:
 - DL transmission: After the wait of SIFS duration (T_{sifs}), MS transmits the MU-DL frame to iRBs on the bandwidth of 20/40/80 MHz. We support MU-DL frame of up to 4 users using PDMA technique. The values of u can be 1, 2, 3 or 4. The duration of DL transmission is denoted by T_{dl} .
 - UL transmission: If iRB successfully receives its data from DL frame, it will respond to MS after T_{sifs}

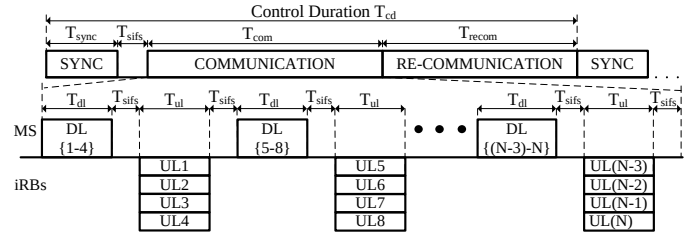


Figure 2. Proposed iWLAN Protocol

by sending UL frame using bandwidth of 20 MHz. Up to 4 iRBs are supported to send their UL frames simultaneously using FDMA technique. The duration of UL transmission is denoted by T_{ul} .

- The DL and UL transmissions are performed until MS finishes sending data to all of N iRBs. An iRB error occurs if the iRB fails to either receive the DL packet from MS or transmit the UL packet to MS.
- Stage 3 (RE-COMMUNICATION): If there are any iRB errors during stage 2, the MS will re-communicate with them again. This re-communication duration is denoted by T_{recom} . The operations during this stage are the same with stage 2. Stage 3 is repeated until MS successfully communicates with all N iRBs or the T_{cd} elapses. When the T_{cd} elapses and there is not any iRB error in this stage, a new T_{cd} is performed.

B. Proposed Multiple-Access Transmission Scheme

In the proposed iWLAN transmission protocol, we employ the MU transmission technique for DL access to enhance the throughput of the FA communication system. The FDMA and SDMA are the conventional transmission techniques which support the MU-DL access. In the proposed iWLAN protocol, because the iRBs receive SYNC frames on channel bandwidth of 20/40/80 MHz, they cannot receive the DL frames on different channel bandwidth by using the conventional FDMA technique.

To support the MU-DL access with low overhead for FA communication systems, the MU-PDMA DL transmission technique is proposed, as shown in Fig. 3. At AP, the MSDU data of up to four users, $MSDU_{(1-4)}$, are merged into one transmission frame, called MU-PDMA. Then, this MU-PDMA frame is sent to all users through one antenna stream on the same channel of up to 80 MHz. This MU-PDMA frame can also be transmitted to all users through four antenna streams to get the diversity gain. For each user, its MSDU is extracted from the received MU-PDMA frame. At the receiver side, the user gets its MSDU based on the User Address and MSDU length field, and then it performs the UL transmission on the channel indicated by the UL Channel field. The UL frame of each user is transmitted on the channel of 20 MHz.

Due to the limitation of hardware connection using up to two SAMTEC cables in this experiment, we present the implementation of 1 AP 2 STAs 20MHz transmission which divides to two groups for 2 STAs in this paper. The results of this implementation can evaluate the grouping transmission of our system.

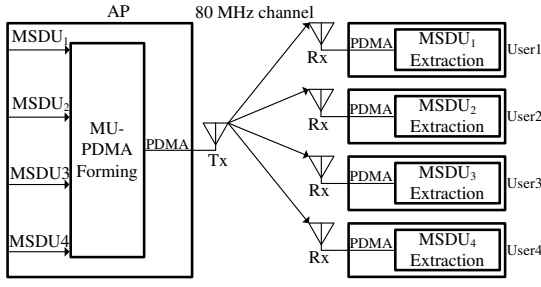


Figure 3. Proposed MU-PDMA DL technique

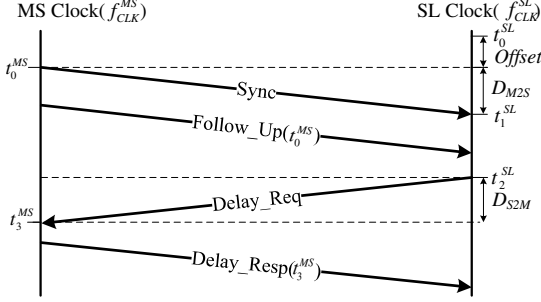


Figure 4. Conventional PTP frame exchanges

III. PRECISION TIME PROTOCOL (PTP)

A. Conventional PTP Protocol

An MS-SL clock system is constructed in the synchronization communication system using the PTP protocol. The MS clock serves as the reference clock. The SL clocks have to trace the timing of the MS clock based on the PTP synchronization protocol. The clock synchronization between the MS and the SL can be done by the exchange of timing messages which are stamped at the MS and SL. The procedure to synchronize the SL clock to the MS clock is shown in Fig. 4. The frequencies of the MS and SL clocks during the synchronization period are denoted by f_{CLK}^{MS} and f_{CLK}^{SL} , respectively. f_{offset} is defined as the frequency offset between SL and MS clocks, then we have

$$f_{offset} = f_{CLK}^{SL} - f_{CLK}^{MS}. \quad (1)$$

The normalized frequency offset (or the clock drift factor) is thus,

$$a = \frac{f_{offset}}{f_{CLK}^{SL}} = \frac{f_{CLK}^{SL} - f_{CLK}^{MS}}{f_{CLK}^{SL}}. \quad (2)$$

The synchronization procedure includes 8 steps:

1. MS sends a Sync message to the SL. The MS stamps and stores the time t_0^{MS} at the moment which the Sync message is completed to send out.
2. SL receives the Sync message transmitted from the MS. SL stamps and stores the time t_1^{SL} at the moment which the Sync message is completed to receive.
3. MS sends a Follow_up message containing the value of the time stamp t_0^{MS} to the SL. SL receives and stores the time stamp t_2^{SL} .
4. SL sends the Delay_Req message to the MS. SL stamps and stores the time t_2^{SL} at the moment which the Delay_Req message is completed to send out.

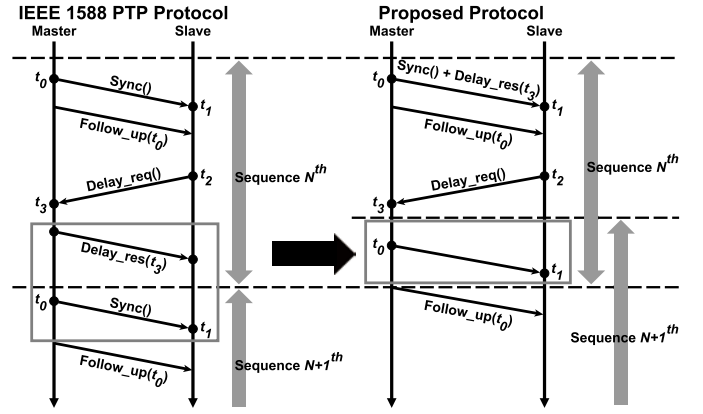


Figure 5. Conventional PTP and proposed PTP

5. MS receives the Delay_Req message transmitted from the SL. MS stamps and stores the time t_3^{MS} at the moment which the Delay_Req message is completed to receive.
6. MS sends a Delay_Res message containing the value of the time stamp t_3^{MS} to the SL. SL receives and stores the time stamp t_3^{MS} .
7. SL calculates the timing offset between its clock and MS clock by following expressions

$$t_1^{SL} = t_0^{MS} + D_{M2S} + a \times (t_1^{SL} - t_0^{SL}) + Offset, \quad (3)$$

$$t_3^{MS} = t_2^{SL} + D_{S2M} - a \times (t_2^{SL} - t_0^{SL}) - Offset, \quad (4)$$

where D_{M2S} and D_{S2M} are the communication path delays from the MS to SL and from the SL to MS, respectively. t_0^{SL} is the time of SL clock when the t_0^{MS} is stamped at MS,

$$t_0^{SL} = t_0^{MS} + Offset. \quad (5)$$

In the conventional PTP protocol, the communication path delay from the MS to SL and the communication path delay from the MS to SL are assumed to be symmetric, i.e. $D_{S2M} = D_{M2S}$. Besides, the clock drift factor is ignored ($a = 0$), i.e. the value of f_{offset} is equal to 0. Then, the value of $Offset$ is derived by

$$Offset = [(t_1^{SL} - t_0^{MS}) - (t_3^{MS} - t_2^{SL})]/2. \quad (6)$$

8. The SL clock is synchronized to the MS clock by calibrating its clock with the value of measured $Offset$ in (6). The synchronization process is repeated after a fixed period.

B. Proposed PTP

In previous research, we have enhanced the conventional IEEE1588 PTP by reducing the frame exchange in one synchronization period as shown in Fig. 5 [12]. By reducing the number of frames, this allows the system to have lesser overhead and probability of error, along with faster processing time. The offset between the MS and SL are calculated using (6). For this implementation system of 1 AP 2 STAs using 20MHz bandwidth, the PTP protocol is presented as Fig. 6. The offset in 1 AP 2 STAs is calculated by

$$Offset_1 = [(t_{1_1}^{SL} - t_0^{MS}) - (t_{3_1}^{MS} - t_{2_1}^{SL})]/2. \quad (7)$$

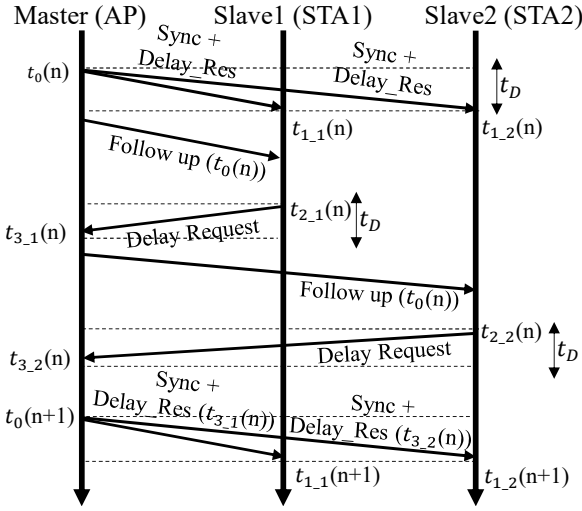


Figure 6. Proposed PTP with 2 groups

$$Offset_2 = [(t_{1_2}^{SL} - t_0^{MS}) - (t_{3_2}^{MS} - t_{2_2}^{SL})]/2. \quad (8)$$

IV. ASYNCHRONOUS COMMUNICATION SYSTEM

In general, there are two types of the communication system when we control iRBs: synchronous communication and asynchronous communication. Synchronous communication is mainly used for industrial Ethernet. On the other hand, there is a system that controls iRBs by asynchronous communication using interfaces such as RS-232C, RS-422, and RS-485. Conventional proposed system supported only synchronous communication due to focusing solely on industrial Ethernet.

Fig. 7 shows a protocol for industrial Ethernet and the proposed system. In this figure, industrial Ethernet and the proposed system communicate alternately in synchronization. AP receives the data for controlling iRBs from MS during the industrial Ethernet communication period. After that, AP transmits the data to STA wirelessly by the proposed system. At the same time, the STA receives the data from AP and transmit to the iRB.

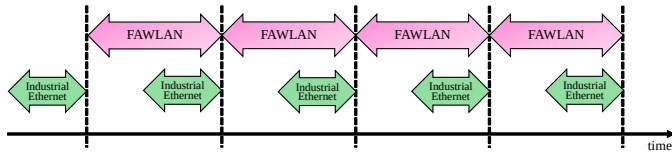


Figure 7. Synchronous Communication

Industrial Ethernet uses not only synchronous communication but also asynchronous communication. Fig. 8 shows a protocol where industrial Ethernet communicate asynchronously, while the proposed iWLAN system performs a synchronous communication. In the case of synchronous communication, AP receives the data entirely before the transmission of the proposed system. On the other hand, in asynchronous communication, AP does not know whether the data is always present before performing communication of iWLAN system. This is a big problem in the conventional iWLAN system, where the system does not support asynchronous communication. The

key to solving this problem is by modifying a mechanism of writing data to memory in the conventional system.

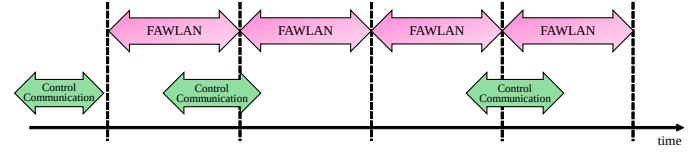


Figure 8. Asynchronous Communication.

Since the data is not transmitted during CPU write cycle, CPU is required to wait until the next communication cycle. Using this method, the AP prevents to deliver the received data to STA immediately. Therefore, we modify the architecture by proposing a memory writing scheme. This modification allows MAC to read the data from memory and transmit it as DL frame, concurrently with writing data cycle.

Fig. 9 shows the data flow of a corresponding modified memory writing scheme. We also modify the software to allow CPU to know the location of memory where MAC can read. It is assumed that AP has wholly received the data immediately after starting communication of the second Control Duration. CPU specifies the memory that MAC reads and writes the data to that memory. MAC reads the data from memory, and generates a DL frame, and sends it to STA. At the next Control Duration, STA's CPU reads the data from memory and sends it to the iRB.

As a result, compared to our conventional systems, it was possible to reduce one control duration from data reception to iRB transmission. On the other hand, this modification causes software complexity. We need to manage memory number on software. However, in FA communication, real-time control is more critical than its complexity.

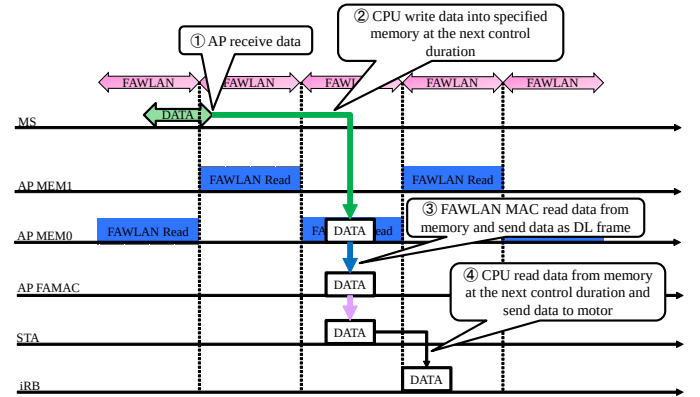


Figure 9. Support Asynchronous Protocol.

V. IMPLEMENTATION RESULTS

A. Motor Control Results

In this section, we present the implementation and verification of the proposed system on FPGA. In the motor control verification, four motors that represent iRBs are connected to two controllers, as shown in Fig. 11. Based on the implementation of one AP two STAs, we connect two STAs to two controllers by using a RS-232C interface. The system is controlled by asynchronous communication. Fig. 12 shows the FPGA platform used for verification. The configuration of the

TABLE 1. Mother board configuration

Name	Specification
Device	StarFire-M820
FPGA	Stratix IV
number of LEs	813.05K

TABLE 2. Daughter board configuration

Name	Specification
Device	Zynq-7030
FPGA	Kintex-7
Logic Cell	125 [KCells]
CPU	ARM Cortex-A9 MPCore
Number of Processor	2

motherboard and daughter board are shown in Table I and Table II, respectively. The implementation of the system on FPGA boards for accurate verification and to test the feasibility of the system in real environments is presented as in Fig. 10.

In this stage of verification, AP and STA are currently connected by wire, instead of using a wireless channel. Fig. 13 shows the motion of the motor. Since the axis of the motor is rotating in order of 1 to 2 to 3 to 4 and four motors are synchronized rotating, we confirm that the iRBs can be controlled by using the proposed system.

B. Time Synchronization Results

In Fig. 14, the trigger observation of time synchronization are shown. Blue triggers are the master, and Yellow triggers are the slave. This result detects multiple triggers and confirms the accuracy of the time synchronization between master and slave. One square represents 40 ns. It has been confirmed that time synchronization is high accuracy from 40 to 100 ns.

VI. CONCLUSION

The proposed design of iWLAN system for iRBs control has been presented in this paper. Our synchronous multi-user iWLAN transmission protocol can achieve the transmission efficiency. The experiment result of the proposed iWLAN system with a programmable logic controller and four industrial robots has shown the capability of control motors of our system in reality. Moreover, the PTP verification result can prove that the system has a high accuracy time synchronization at nano-second which is from 40ns to 100ns. In future work, full implementation and evaluation combining with radio frequency (RF) will be deployed in the near future.

ACKNOWLEDGMENT

It is research and development by the Japan Ministry of Economy, Trade, and Industry Sapoin project (strategic fundamental technology advancement support project).

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Figure 10. FPGA implementation for communication of AP and 2 STAs

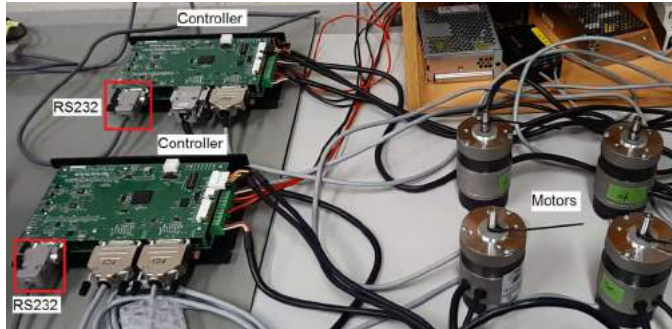


Figure 11. Wired system communicated with RS-232C.

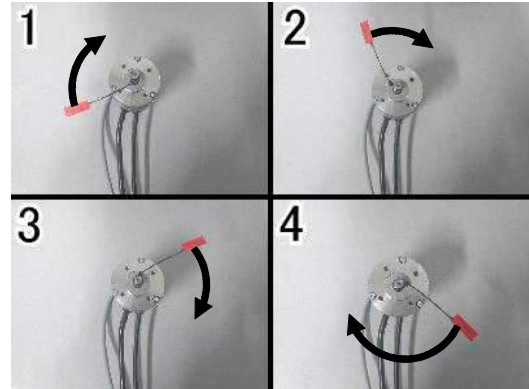


Figure 13. Result of motor control with proposed iWLAN system

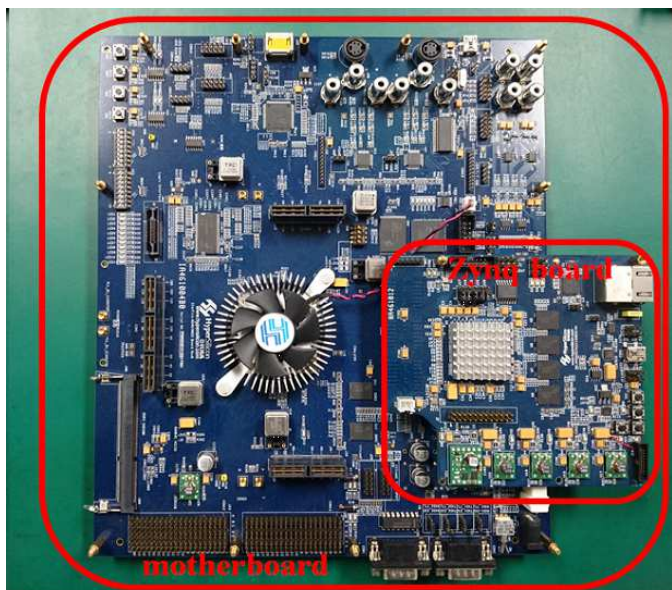


Figure 12. FPGA platform.

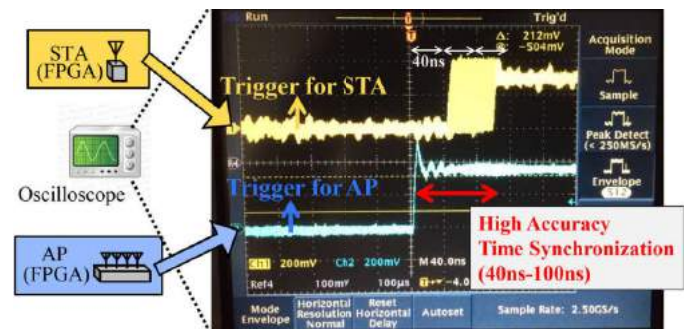


Figure 14. Time synchronization result on oscilloscope.



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